RPO Safety Task Force – Draft Safety Recommendations for End Users

This is a CONFERS draft document consisting of safety recommendations for parties interested in setting up a Rendezvous and Proximity Operations (RPO) mission between a Servicer Spacecraft and a Client Space Object (CSO) including derelict or debris objects. The end users of this document are intended to be the operators of a Servicer Spacecraft and a Client Space Object involved in an RPO mission. Following these guidelines may be helpful as the end users to creates an Interface Control Document (ICD) or operations document for the intended close approach and/or dock with their spacecraft or platform.

This document is designed to provide industry-derived recommendations that may assist operators in making decisions about their RPO process informed by safety principles and guidelines put forth by the CONFERS RPO Safety Task Force.

Along with these guidelines, a set of reference missions and lexicon definitions are provided to aid the user. This document is not meant to be comprehensive but rather informative and each user is expected to tailor their ICD and operational documents to their particular mission need. Some questions are intended for operators of the Servicer Spacecraft to ask operators of the CSO, and some are meant to be communicated by the operators of the Servicer Spacecraft to the operators of the CSO. CONFERS emphasizes that while these guidelines are meant to serve as a resource to be referenced or emulated, satellite operators also are responsible for compliance with legal obligations including obtaining proper licenses for all operations in advance of the proposed mission(s).

This document is based on best practices and lessons learned from existing RPO missions. A list of referenced missions can be found in Appendix 4.2.

Disclaimer

This document has been developed by the CONFERS Rendezvous and Proximity Operations (RPO) Safety Task Force ("Task Force") through a collaborative industry member process. It reflects the collective recommendations and consensus views of the Task Force at the time of publication. The contents of this document should not be interpreted as representing the views, positions, policies, or technical approaches of each or every CONFERS member organization, nor does publication imply endorsement by any individual member.

The recommendations contained herein have been developed using the expertise of Task Force participants together with information derived from publicly available technical literature, published standards, government guidance, mission reports, and publicly available mission data. While CONFERS has made reasonable efforts to ensure the accuracy and completeness of this information, it does not warrant that the information is complete, current, or free from error.

This document does not contain export control information.

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1 Scope

The scope of this document and the associated voluntary safety recommendations apply to a subset of the CONFERS On Orbit Servicing (OOS) Mission Functional Diagram, as seen in Figure 1 below. Specifically, this document is meant to inform guidelines and best practices for *RPO Safety,* including *Servicer Early Orbit Checkout* (4.2), Orbital Servicing Ops (5.2, 6.2, 7.1, 7.5), *Inspection-Only Option* (7.6), *and Release & Departure* (10). Refer to the CONFERS publication [CONFERS On-Orbit Satellite Servicing Mission Phases] for more details on this diagram and the definitions for each.
This document is intended for use with uncrewed RPO, as there is sufficient work done to define RPO for crewed spacecraft.

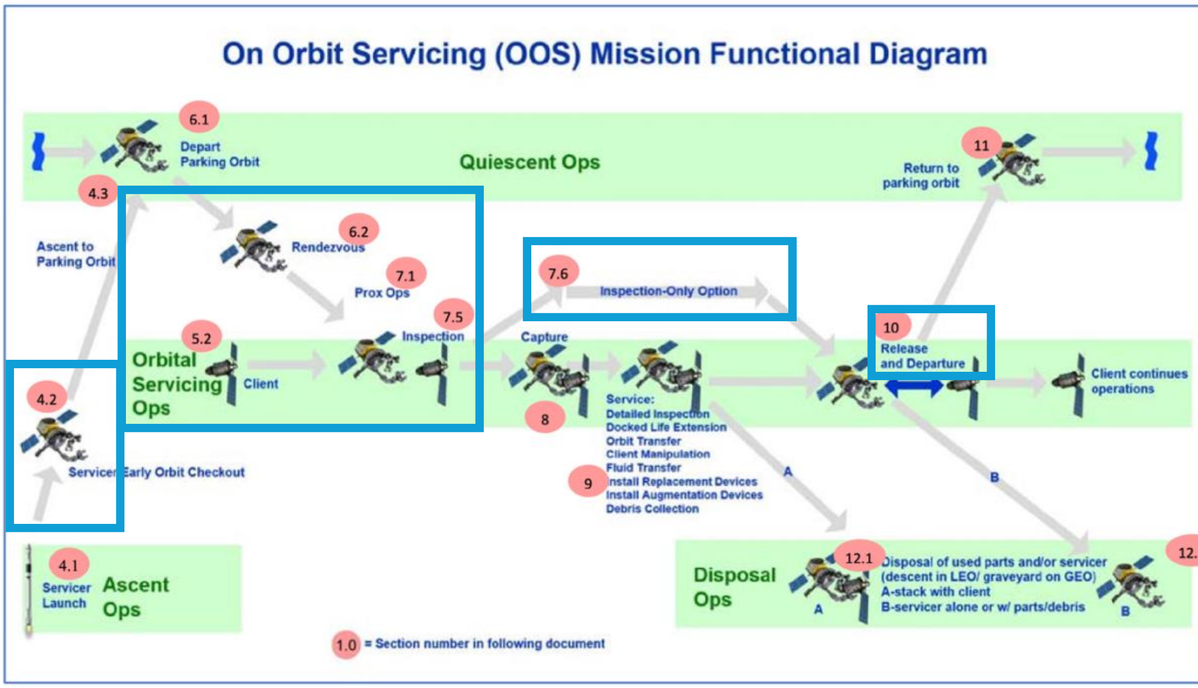

Figure 1: CONFERS OOS Mission Functional Diagram (From ISO 24330)

This document dovetails with existing standards AIAA S-158 (Free-Flyer Capture) and AIAA S-155 (Spacecraft Fiducial Markers), covering mission functions 8 and 9 in the diagram above. It is recommended for the reader to familiarize themselves with both of these standards for a full mission design.

2 Definitions

2.1 New Definitions (to add to CONFERS lexicon)

Absolute Navigation: Determining a spacecraft's position, velocity, and/or orbit relative to the center of the Earth (or another well-defined inertial reference frame for non-earth-orbiting missions).
Active Abort: An abort action which requires a propulsive maneuver or a change in attitude
Approach: The final phase of RPO within the Keep-Out Volume ending in close proximity to the CSO.
Approach Corridor: A 3-D volume in space inside the keep-out volume within which the servicer spacecraft approaches the Client Space Object.
Autonomous: Able to carry out tasks and adapt to new information without direct human guidance or intervention
Collision: Physical contact that results in operational failure or degradation of either object and/or the creation of orbital debris that poses a significant risk to other space objects.
Departure: The phase of RPO of separation to a safe distance before resuming independent operations.
Hold: A pause or delay in rendezvous operations where the Servicer maintains its relative position with respect to the CSO such that it neither approaches nor retreats from the CSO.
Passive Abort: An abort action which does not require a propulsive maneuver or a change in attitude
Proximity Operations Control Volume: volume of space established for non-interference and to assure relative navigation control while the servicer spacecraft and client space object are within close proximity
Relative Navigation Sensors: Sensors used to determine relative position, velocity, or attitude (pose) between two spacecraft.
Relative Navigation: The determination of position, velocity, and attitude with relation to a defined client space object or point in space.
RPO Active Safety: The capability to deliberately execute collision avoidance actions in order to prevent collision or unintended contact with the CSO.
RPO Environmental Safety: The process of minimizing risks to spacecraft, astronauts, and infrastructure operating in orbit.
RPO Mission Safety: The process for safe execution of an RPO mission between a Servicer Spacecraft and Client Space Object.
RPO Safety: The process of ensuring that a set of maneuvers or actions does not bring harm to the Servicer Spacecraft or Client Space Object, and includes RPO Mission Safety and RPO Environmental Safety.
Waypoint: A waypoint is a point or region that forms the designated transition between two or more Control Volumes.

2.2 Existing Definitions

Abort (from CONFERS lexicon): An action which stops an on-board process and, if necessary, initiates an alternate process to put the Servicer Spacecraft and Client Space Object in a safe and collision-free state.
Client Space Object (from CONFERS Lexicon): The space object being serviced by the Servicer Spacecraft.
Collision Avoidance Maneuver (from CONFERS lexicon): An operation executed by a space object relative to another space object to avoid contact for a specified amount of time.

Control Volume (from CONFERS lexicon): Volume of space established for non-interference and to assure relative navigation control while the Servicer Spacecraft and CSO are within close proximity.

Fiducial Markers (from Draft AIAA S-155 Spacecraft Fiducial Markers):
An object placed in the field of view of an imaging system, for use as a point of reference or a measure, and for alignment in preparation for On-orbit/In-space Servicing.

Free-drift (from Draft AIAA S-158 Free Flyer Capture): The state of motion of an object in orbit whereby constant attitude is not maintained. When attitude and position control is disabled, the object is said to be in free-drift.

Keep Out Volume (from Draft AIAA S-158): A minimum 3-D volume of space around the Client Space Object defined based on navigational uncertainty of each Rendezvous, Proximity Operations and Docking phase or any additional operational volume into which a Servicer Spacecraft may not enter without approval.

Passively Safe Trajectory (from CONFERS Lexicon): A trajectory which will not interfere with a convex envelope, volume, zone or any area defined to avoid contact with sufficient margin relative to the client space object when control is lost, over a specified duration.

Prepared (from CONFERS lexicon): spacecraft equipped with interfaces and accommodations intentionally designed to enable in-space servicing.

Proximity Operations (from CONFERS lexicon): Series of orbital maneuvers executed to place and maintain a spacecraft in the vicinity of another space object (artificial or natural bodies) on a relative planned path for a specific time duration to accomplish mission objectives.

Rendezvous (from CONFERS lexicon): Process wherein two space objects (artificial or natural body) are intentionally brought close together through a series of orbital maneuvers at a planned time and place.

Servicer Spacecraft (from CONFERS Lexicon): Spacecraft performing the On-Orbit Servicing action.

3 Recommendations for Spacecraft RPO Best Practices

The following considerations form a set of (non-exhaustive) voluntary guidelines for RPO Safety. The CONFERS RPO Safety Task Force recommends that missions performing robotic RPO utilize this in a framework, building on lessons learned from 50 years of spaceflight.[1,2]
Section 3.1 covers general topics which pertain to all aspects of the CONFERS OOS Mission Phases, encompassing *Rendezvous* and *Proximity Operations*. Sections 3.4 through 3.7 cover specific topics related to each phase of the CONFERS OOS Mission Phases which this document pertains to.

3.1 General RPO Considerations

3.1.1 CONOPS Definition

Clearly identify the CONOPS for the mission. Define where the mission begins, where it ends, and what the key Waypoints are in-between. Define any allowance for aborts and hold points. The CONOPS should address who is in control of each spacecraft, how they communicate and coordinate, how go/no-go decisions are made and how authorization to proceed is approved and communicated, a simulation of the RPO, a detailed timeline of events including the relative positions of the two vehicles, etc. It is recommended that the user familiarize themselves with the NASA Systems Engineering Handbook, INCOSE SE handbook, and CONFERS Publication ISO 24330 (Space Systems – RPO & OOS Programmatic Principles and Practices) for guidelines and standards on CONOPs generation.
The complexity of RPO lends itself to the use of modern systems engineering tools such as analysis within a modeling environment that considers orbits, sun angle, and other considerations for planning orbital maneuvers. This will enable simulation of nominal and off-nominal scenarios. This can determine the probability of success or failure within a nominal plan in the face of errors.

3.1.2 Approach Trajectories

Clearly identify the trajectories used for Approach. Commonly used approach methodologies make use of R-bar or V-bar approaches, with each having their own advantages and disadvantages, including but not limited to: availability or lack of passively-safe waypoints, solar incidence angles / backlighting, fuel efficiency vs maneuver time, plume impingement risks, etc. When creating approach trajectories, users should be familiar with existing methodologies, the advantages and drawbacks of each, and past mission lessons learned to inform their decisions[3,4,5]

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[1] Barnhart, David A., and Rahul Rughani. "On-orbit servicing ontology applied to recommended standards for satellites in earth orbit." *Journal of Space Safety Engineering* 7.1 (2020): 83-98.

[2] Barnhart, David A., et al. "Using historical practices to develop safety standards for cooperative on-orbit rendezvous and proximity operations." *69th International Astronautical Congress (IAC), Bremen, Germany*. 2018.

[3] Getting in Your Space: Learning from Past Rendezvous & Proximity Operations https://aerospace.org/sites/default/files/2018-05/GettingInYourSpace.pdf

[4] On-Orbit Servicing Ontology applied to Recommended Standards for Satellites in Earth Orbit https://www.sciencedirect.com/science/article/abs/pii/S2468896720300094

[5] Proximity Approaches and Design Strategies for Non-Cooperative Rendezvous* V-bar Hopping vs. Spiral Approach https://www.jstage.jst.go.jp/article/tjsass/64/3/64_T-20-6/_pdf

3.1.3 Control Volumes

Define the Control Volumes for the spacecraft involved in the RPO maneuver. Refer to appendix for examples. Proper definitions of Control Volumes are recommended to clearly delineate the handoff between mission phases.[6] Define available sensors and abort modes. Define the allowed approach velocities for each waypoint or zone. Define the entrance criteria to progress between Control Volumes during the approach sequence. Identify which of these (if any) require ground approval.

If waypoints are in use, define how they are handled by the abort modes. Define clearly with a diagram or flowchart how the spacecraft proceeds through the set of waypoints, and what prevents the spacecraft from skipping past or circumventing a waypoint.

Define any control volumes used that apply to the approach or retreat, such as an Approach Volume, and what approval process is required for safe operations by the CSO. The size/shape should defined by the constraints that the CSO needs the Servicer to stay within and can take into account drift, navigation accuracy, etc., but the space itself should be defined by the CSO and should be relative to the CSO (in an inertial frame or body-fixed frame, depending on the mission).

3.1.4 Abort Modes and Holds

For a planned approach sequence, list the criteria that would trigger an abort or hold. Define the abort states for each criterion. Determine whether aborts are Active or Passive. Passively safe trajectories typically allow for passive aborts~~.~~ Abort modes may vary between orbit types (i.e., move above while at GEO), and will depend on other variables, such as the presence of other objects in the vicinity of the Servicer and CSO. Define for each abort state or hold whether it is triggered manually or automatically.

RPO Active Safety is the capability to deliberately execute collision avoidance actions in order to prevent collision or unintended contact with the CSO. This includes, but is not limited to, the execution of emergency braking maneuvers or dedicated collision avoidance maneuvers initiated in response to detected hazards or off-nominal conditions.

When creating abort modes and holds, consider the following three types of responses to a safety violation:

1. Wait for more information
2. Continue the course (do nothing to change trajectory, or do not execute the planned operation – e.g. a robotic operation)
3. Execute a corrective maneuver or revert to a fallback state

Option 1 is for instances when the safety violation may be temporary and where there is sufficient time to recover. This option also gives the ground ~~more~~ opportunity for additional analysis. Logic could be added to any on-board safety system to determine how long the vehicle may stay in this mode before escalating to a different response mode.

Option 2 is implemented when the safety violation can be determined to be either of acceptable risk, or of a lower risk than a corrective maneuver. This option should include a response time limitation, as it is better to do nothing if there isn't sufficient time to plan a new maneuver.

Option 3 Is often considered a last resort since every maneuver can introduce additional uncertainties or may be responding to bad state information. The FDIR system and trajectory should be designed such that abort maneuvers can be executed safely. Some conditions could be pre-programed that would result in a known safe trajectory. Consider the Control Volume that the

[6] NASA Orbital Express Rendezvous Lessons Learned https://ntrs.nasa.gov/api/citations/20110011506/downloads/20110011506.pdf

spacecraft are in when defining the abort trajectory, and whether the abort will move into a more or less restrictive Control Volume
After completing an abort sequence, identify the steps required to resume the mission. Consider the new relative position and orientation of the Servicer Spacecraft and Client Space Object, as well as external influences like the Sun.

It is recommended that a point of no return be defined after which special care must be given for Abort cases and conditions leading up to the capture process. This should be done in accordance with AIAA S-158 (Free Flyer Capture). Typically this point can be a few meters to a few dozen meters from the CSO, and can coincide with the keep-out sphere or be further out. The purpose of this is to shift to a more conservative set of abort procedures which should be tied in closely with the Servicer's FDIR for automated abort triggering in close proximity based on pre-determined criteria. For example, in close vicinity of the client, even rotation of the servicer can cause inadvertent contact of deployed appendages with the CSO. If the Servicer has robotic arms, the coordinated movement of the arm along with the Servicer spacecraft should be taken into account for this abort planning.

3.1.5 Autonomy

Spacecraft autonomy can be useful to address faults or perform a sequence of automated task transitions without input from the ground. Depending on how it is implemented, adding autonomy may increase or decrease a mission's degree of RPO safety. For example, during the Orbital Express mission, the autonomous abort was intended to place the spacecraft in a stable hold, however due to an unexpected drift rate, this hold was not as stable as predicted[7]. When using autonomy, it is recommended to have pauses and human supervision for initial trial runs before reducing the supervision to zero to become fully autonomous. It is recommended that autonomy be tied in with the spacecraft's Fault Detection, Isolation, and Recovery (FDIR) system to enable logic for autonomous diagnostic and recovery during critical RPO mission operations.

3.1.6 Fault Tolerance

Fault tolerance for spacecraft RPO is a critical design requirement that ensures the mission can continue safely, or reach a safe state, despite component or software failures. Key strategies may involve hardware and software redundancy, autonomous fault management, and specific operational procedures, including Fail Safe and Fail Operational modes.
Define in advance the number and types of of faults that the system must tolerate to meet its specifications, and the associated recovery strategies. For example, a single fault tolerant approach should still be able to meet its RPO Mission Safety requirements after a single fault. After any fault, it is still recommended to make an assessment of safety and procedures before proceeding.

Consider how fault tolerance will affect the ability to complete maneuvers, particularly abort maeuvering. It is recommended that mission critical systems such as the propulsion system used for RPO and the relative nagivation sensors, among other, be multi-fault tolerant to enable the spacecraft to avoid a collision when in close proximity. If there is a fault that removes the Servicer's ability to react to or avoid a collision with the CSO, then the results could be catastrophic to the mission.

[7] Dennehy, C. J., & Carpenter, J. R. (2011). *A summary of the rendezvous, proximity operations, docking, and undocking (rpodu) lessons learned from the defense advanced research project agency (darpa) orbital express (oe) demonstration system mission* (No. NESC-RP-10-00628).

3.1.7 Risk Tolerance

Risk tolerance for the mission should be defined in advance. Define how the risk is being quantified and computed. Identify how the risk tolerance and computations vary between Rendezvous, Proximity Operations, and Docking (RPOD). Identify the relationship between the Risk Tolerance and Fault Tolerance for this mission.

Expand to talk about Class A vs Class D missions for risk tolerance. High value asset vs low value asset. Manned platform? How does this change with regard to the orbital regime (i.e. above or below ISS, GEO graveyard). VLEO = sandbox. Check for literature on sensitivity of orbital regimes w.r.t. orbital debris. ISO standards (i.e. better to test in graveyard than GEO belt).

3.1.8 Safety

Safety for RPO can be two categories: mission safety and environmental safety.
As defined in section 2.1, *RPO Mission Safety* is the process for safe execution of an RPO mission between a Servicer Spacecraft and Client Space Object. This may be achieved through relative-motion trajectories, by selecting a trajectory or series of trajectories that ensure no unintentional contact between the Servicer Spacecraft and Client Space Object while in free-flight until the Keep Out Volume entry maneuver is initiated. RPO Mission Safety includes all types of attributes that may cause interference or damage between the Servicer Spacecraft and Client Space Object. This includes, but is not limited to:

- electromagnetic interference (EMI)
- thermal mismatches
- plume impingement
- power generation interruption
- possible electrostatic discharge (if the two spacecraft have not equalized their potentials), etc.

Ensuring that servicing missions do not affect third party spacecraft is fundamental to building trust across the broader space ecosystem. As in-space servicing becomes more common, operators, governments, and commercial partners must have confidence that these missions can be conducted safely, transparently, and predictably. Establishing rigorous non-interference protocols, situational awareness capabilities, and verification processes will enable scalable servicing architectures while maintaining the stability, safety, and sustainability of the orbital environment for all users.

As defined in section 2.1, *RPO Environmental Safety* is the process of minimizing risks to spacecraft, astronauts, and infrastructure operating in orbit. It is important to ensure that any actions taken as part of the servicing mission do not affect the space environment. This translates to limiting the risk of inadvertent release of free-floating uncontrolled debris resulting from the Servicing mission, reducing the probability of collision between the Servicer Spacecraft and the Client Space Object, and preventing damage during RPO and servicing operations that could disable either spacecraft. It is important to ensure that any actions taken as part of the servicing mission do not affect third party spacecraft. This can be done by following existing rules/regulations and international norms for orbital debris mitigation, and ensuring that emitting devices (radios, lasers) aren't pointing at third-party spacecraft in close proximity while in operation. This includes compliance with the US Obribal Debris Mitigation Standard Practices and similar national and international buidance.

3.1.9 Transparency

The servicer and client conducting servicing operations should work within the principle of transparency to promote safety and trust, by employing notification to states, and communications with entities, notification protocols. This includes complying with the UNOOSA Convention on Registration of Objects Launched Into Outer Space[8], as implemented by the registering State affiliated with the spacecraft operator. There may be additional requirements set by the registering State, the spacecraft operator should research these within their own jurisdiction.

The servicer should define the means and procedures for providing main features of the operational plan and associated information to other spacecraft operators. This could include the type of on-orbit servicing to be performed, the client object, the entity providing the service, basic orbital parameters, the period of the sequence from rendezvous to separation, SSA organizations to be informed of servicer's ephemeris, and the information disclosure policy in the event of emergency.

3.1.10 Coordinate Systems

Define the coordinate system(s) in use. Provide a definition of the spacecraft's absolute and relative-motion coordinate systems, and the expected attitude state(s) of the spacecraft in all of its operational modes throughout the RPO process.

3.1.11 RPO Sensors

Define the RPO sensors and their full specification for each sensor in use by the Servicer Spacecraft. Many sensors used for relative navigation produce data that needs further interpretation through algorithms, and might use different algorithms at different ranges. For RPO consider the effects of range and lighting conditions on processing, latency, update rates, precision, etc.

For example, use of differential signals from GNSS receivers onboard the two spacecraft can serve as relative measurements in an accelerating or rotating reference frame rather than measurements in an inertial reference frame. Relative navigation sensors can include but are not necessarily limited to passive sensors such as visible and infrared cameras, as well as active sensors like LIDAR, Radar, etc., and may be coupled with real-time or near-real-time software capable of converting the raw measurements into relative position (bearing/direction and range), velocity, or attitude (pose) data.

3.1.12 Ground Communications

Define the method of communication between the two Mission Operations Centers (MOCs) on the ground during the proposed RPO mission. Realtime comms between MOCs are recommended during RPOD for increased safety.
Define whether or not the Servicer Spacecraft's MOC will have continuous communications with the Servicer Spacecraft during key events, including transitions between ~~zones~~ waypoints.

3.1.13 Crosslinks

Define any crosslinks between the Servicer Spacecraft and Client Space Object. Identify the role that the crosslinks will provide for RPO safety, and what information will be communicated. It is recommended to adhere to CCSDS standards for exchanging satellite position data in crosslinks.

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[8] https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/registration-convention.html

3.1.14 Mission Operations Control

It is recommended that the Servicer Spacecraft's ground operations team and MOC have control authority for the servicing mission from the point that the Client Space Object enters free-drift mode (or another off-nominal mode for close approach). If this is not the case, justify. If a protocol is in place for MOC to MOC communication, its recommended that the operations team rehearse these communication protocols and safety procedures in advance of the mission.

3.1.15 RPO System Qualification and Testing

Prior to in-flight operations, operators may wish to conduct a ground campaign for RPO system qualification. Qualification may include analysis, simulation, or testing, as appropriate to the operator's particular system. Simulation tools available on the open market or in-house simulators may be useful for this. Operators may also wish to engage in hardware testing depending on their unique needs[9].

3.2 Phase 4.2: Servicer System-level Spacecraft RPO capability checkout

Many RPO systems cannot be adequately checked out on the ground, or cannot be properly evaluated without another object to test against. Before conducting rendezvous operations CONFERS RPO Safety Task Force recommends operators consider the following:

1. Build upon existing Launch and Early Operations (LEOPS) testing.
2. Maneuvering and navigation checkout: verify planned vs. actual orbital maneuver capabilities. Verify navigation accuracy before and after a maneuver.
3. RPO sensor capabilities: Conduct orbital characterization checks of the sensors including the ability to acquire, track, and determine range to another object. Conduct testing in multiple lighting conditions and at various ranges. Consider the types of testing done for star trackers and imaging sensors and apply these same methodologies to test RPO sensor systems.[10] Compare sensor readings with other sensors aboard the spacecraft to see if they sync up.
4. Consider using objects of opportunity in the vicinity of the Servicer Spacecraft, if available, to image and test/calibrate optical sensors. Alternatively, consider deploying a visual target of known parameters, on a boom or tether, to use as a calibration target for optical sensor calibration.

3.2.1 Pre-RPO On Orbit Test Plan Considerations

Define the plan for dry runs and incremental CONOPs demonstrations prior to a full run-through of the RPO sequence. It is recommended to perform dry runs both on the ground and in-orbit prior to an RPO mission with a Client spacecraft. Ground testing should utilize a testbed capable of at least 3 Degree of Freedom (DoF) dynamic motion, with a 6DoF testbed preferred. A preliminary list of testbeds can be found in the Appendix. Missions useing optical RPO sensing systems should be tested in realistic lighting conditions, with real-life visuals. If the overall mission includes docking, then the user can consider combining this testing with the cking hardware validation in a contact dynamics facility, per recommendations set out in AIAA S-158[11]. The CONFERS RPO Safety Task Force

[9] See the Appendix for more details on available testbeds additional resources.

[10] Markley, F. Landis "Attitude determination using vector observations: A fast optimal matrix algorithm." *Flight Mechanics (Estimation Theory Symposium, 1992.* 1993

[11] Note that while this should be performed in tandem with validation and verification of the docking and capture mechanisms (if present), that is out of scope for this document. The user should refer to AIAA S-158 (Free-Flyer Capture) for guidelines on those subsystem checkouts.

recommends that authors consider their unique mission CONOPS and develop a test plan tailored to their needs. As a service to the industry, resources to aid in this are provided in the appendix.

It is recommended that the on-orbit test plan include the following elements:

1. System Health Check: Verify health and status of all RPO relevant systems (e.g. navigation, guidance, attitude determination, attitude control, propulsion, RPO sensors, computer vision, communication, and fault protection).
2. RPO Sensor Calibration: Perform any necessary calibration to ensure optimal functionality in the relevant environment.
3. Acquisition and Tracking Check: Verify acquisition capability, object tracking capability, computer vision, etc. Verify propagation capability and reacquisition by identifying and tracking multiple objects, turning away (loss of custody) for some period and reacquiring. This can be done with a deployable target, a nearby object of opportunity, or the Client spacecraft (if within range).

3.3 Phase 5.2: Client Operations Pre-Servicing

This section applies only to active Client Space Objects. If the Client is derelict or debris, skip this section, and reference the CONFERS Active Debris Remediation document for more details.[12]

3.3.1 Assess the initial Health and Status of Client

Perform subsystem and system-level checks of the Client spacecraft to assess its current operational health and status. Determine if any of its operational modes are restricted. Characterize its control authority. These tests should draw on functional validation tests done when commissioning the spacecraft, to compare and contrast, identifying degradation of critical systems. This will then inform the Servicing CONOPs whether or not the planned maneuvers are feasible.

3.3.2 Client Space Object Repositioning

Determine whether or not the Client Space Object will be repositioning from its normal operating orbit to prepare for the Servicer Spacecraft's Rendezvous. If so, define the trajectory and timeline for this operation.
In the case that a servicing operation is interrupted or aborted, identify the actions to be taken by the Client Space Object to reset for the next opportunity. Clearly list these steps in the CONOPS and align them with those of the Servicer Spacecraft's CONOPS.

3.3.3 Client Sensors Useful for RPO

Identify any sensors on the Client spacecraft that will be used during RPO. While it's not necessary that all sensors be made available for use by the Servicing Spacecraft's operators, knowledge of all available sensors can be critical during time-critical anomaly resolution. These sensors could include: star trackers, space-domain awareness (SDA) sensors, cameras, earth-horizon sensors, etc.

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[12] Maclay, Timothy, et al. "Application of Debris Mitigation Standards to Active Debris Removal Missions: Findings and Recommendations from CONFERS" *76th International Astronautical Congress (IAC), Sydney, Australia*. 2025.

3.3.4 Client's Communication Capabilities

Define the communications capability of the CSO. Identify any real-time or intermittent communications with the ground. Identify any crosslink capability between the Servicer Spacecraft and Client Space Object. If crosslinks are expected to be used, define the timeline, frequencies, etc. such that the CONOP is clear and agreed to by both parties in advance.

3.3.5 Client Space Object Operational Considerations

Identify the operational mode(s) of the Client Space Object during RPO. Determine whether the Client Space Object will be in a passive mode (Free Flight) of operations. Identify whether repositioning or reorienting of appendages are required. Identify the the solar array pointing angles throughout the operation and what the power state of the Client will be (if known). Consider whether the Servicer Spacecraft will cast a shadow on the Client Space Object, or vice-versa, this could diminish its power input or block line-of-sight for critical sun or earth horizon sensors. Consider also whether or not casting a shadow could trigger an automatic FDIR response, should the CSO not be entirely de-activated

Identify the thermal modes for the Client Space Object during the proposed operations and how RPO will affect its ability to reject waste heat. Consider the possibility of thruster plume impingement from the Servicer onto the Client, or vice versa. Consider potential RF/EMI interference between the the Servicer and the Client. Identify whether the operational modes of the Client need to be modified to address these potentially negative interactions.

Define at what point during the RPO sequence the Client Space Object will transition into an off-nominal operational state. To enable inspection, it's recommended that the Client Space Object enter such a state where its GNC system won't be maneuvering unpredictably while the Servicer is in proximity. For inspection, predictable maneuvering could be no maneuvering at all, maneuvering to keep fiducials in line of sight of the Servicer, maneuvering to match lighting conditions for optics, etc. Maneuvering includes both planned maneuvers and abort maneuvers.

3.3.6 Client Status Monitoring

Define what status monitoring of the Client Space Object is available during the RPO process. Identify what health and status data is being broadcast by the Client (if any) and who will be monitoring the CSO. If possible, the client spacecraft should use a crosslink to communicate its attitude and inertial position from GNSS, if available, with the Servicer.

3.4 Phase 6.2: Rendezvous

The extent of the rendezvous phase varies from mission to mission; However, passive safety trajectories are typically available during the rendezvous phase. In the start of the Rendezvous phase, ground measurements and other absolute positioning tools are generally used for guidance. Before transitioning to proximity operations, navigation should switch over to relative measurements when such measurements exceed the accuracy of absolute measurements (measurements in an inertial reference frame).

3.4.1 Transition between Absolute and Relative Navigation

The transition point between absolute and relative navigation should be defined in the CONOPS. Identify the methodology used to minimize the positional errors during the transition. Define the minimum and maximum range for which the relative navigation system is viable. Relative navigation data is typically obtained by the servicer spaceraft, but in situations where an operational CSO has the appropriate sensors, data collected by both spacecraft may be used. One commonly used criterion for transition is when the Servicer's sensors can see the CSO to measure relative distance and pose by on-board RPO sensors.

Define the minimum range at which absolute navigation is viable. This is typically obtained from ground-based sensors, earth-station ranging, or via a GNSS receiver onboard the spacecraft. Clearly define the overlap (if available) in the sensing regimes to ensure a smooth transition between sensors. It is recommended to have an overlap between sensors to allow validation at the transition between sensing regimes. Refer to Figure 2 in the Appendix.

3.4.2 Transition between Active and Passively Safe Trajectories

Define how the spacecraft transitions from an actively safe trajectory (where safety is achieved through defined abort modes) to a passively safe trajectory, and vice-versa. Identify the criteria needed to achieve this transition. Define the designated control volumes (if any) where this is permitted to occur, or control volumes where this is prohibited. Note that after transitioning from rendezvous to proximity operations, passive safety may not be available due to its higher costs compared to other safety measures, such as aborts and holds.

3.4.3 Transition to Proximity Operations

Define the operational conditions and the communications with the Client Space Object that are required for go/no-go before transitioning to proximity operations, and what criteria qualify for an abort. List abort modes and recovery CONOPs.
Servicer Spacecraft and/or Client Space Object operators should notify appropriate bodies that are monitoring conjunctions that the RPO will be occurring, before passing the conjunction threshold. It may additionally be useful for the Servicer to monitor CSO conjunction alerts when entering into proximity operations.

3.5 Phase 7.1: Proximity Operations (Prox Ops)

CONFERS defines Proximity Operations as "[a] Series of orbital maneuvers executed to place and maintain a spacecraft in the vicinity of another space object (artificial or natural bodies) on a relative planned path for a specific time duration to accomplish mission objectives."

While the range at which operations switch from rendezvous to proximity operations varies on a mission-to-mission basis, it is typically demarcated by the Servicing Spacecraft's sensing capability, and the Client Space Object's keep-out zones. In the proximity operations phase, it will be possible to determine the relative pose of the CSO from the Servicer Spacecraft (see Section 3.4.1). This transition is recommended to be no less than 1000m in LEO[13], and can typically be on the order of 5-10 km. This is a typical distance used for conjunction alerts in LEO. In GEO, this is typically on the order of 30km.[14]

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[13] International Rendezvous System Interoperability Standards (IRSIS) https://internationaldeepspacestandards.com/wp-content/uploads/2024/02/rendezvous_baseline_final_3-2019.pdf

[14] Pyrak, Matt, and Joseph Anderson. "Performance of Northrop Grumman's mission extension vehicle (MEV) RPO imagers at GEO." *Autonomous systems: Sensors, processing and security for ground, air, sea and space vehicles and infrastructure 2022*. Vol. 12115. SPIE, 2022. https://amostech.com/TechnicalPapers/2021/Poster/Pyrak.pdf

For unmanned RPO with crewed commercial space stations, where the station is the Client Space Object, in addition to the guidance provided in this document, it is important to note that there will likely be additional levels of safety procedures required because of the station's manned rating, similar to that of the ISS approach guidelines. There will likely be a lower risk tolerance, and more scrutiny on the approach planning.

3.5.1 Dry Run / Calibration

It is recommended to perform a calibration dry-run where the Servicer approaches the Client without entering the keep-out zone to test the RPO sensors and subsystems and if possible comparing the results reported by the in-space vehicles with results from an external truth source. This can be done by approaching towards the first hold point, and then initiating a hold until the operations team can analyze data on the ground to ensure the maneuver executed as expected. This is highly encouraged each time a new CONOPs is attempted. If a dry run is not performed, provide justification.
Similarly, Fiducials & Camera Systems should be tested when the Servicer is in appropriate range of the Client Space Object.

It is recommended that the dry run / calibration test plan include the following elements:

1. Relative Navigation Check: transition to relative navigation and verify planned vs. actual relative navigation orbit. Verify relative navigation sensor performance and algorithm performance, and corellate with ground data if possible.
2. Transition Between Sensing Regimes Check: In test ranges where multiple sensing systems can function at the same time, these values should be compared to each other for corroboration.
3. Crosslink Check: If there are bidirectional communications systems in place for cooperative RPO, these should be tested prior to proximity operations. As these crosslink communications may have a limited range, this may not be possible to test until midway through the approach sequence. Be sure to identify appropriate hold points in the CONOPs to allow for this.
4. Telemetry Beacon Check: If telemetry beacons are being used as part of the RPO CONOPs, these should be tested at their expected operating range(s).

3.5.2 Transition Between Control Volumes

Define the rules that govern transition between waypoints and control volumes. Define the go/no-go criteria, and what initiates an abort maneuver. Identify which of these require ground verification, and what verification is required for mode transitions. Identify any real-time communications available for the ground to verify these points.

3.5.3 Proximity Operations Duration and Hold Points

Define the duration of the proximity operations phase, and how this phase is managed by ground operators. Identify whether the proximity operations phase is continuous or if there are allowable safe hold points to allow the ground team to troubleshoot issues.

3.5.4 Pose Estimation and Control Volumes

Define at what separation distance the knowledge of the pose of the Client Space Object becomes critical. Identify any appendages and protrusions which are present on each spacecraft that could impinge during proximity operations. A clear definition of Control Volumes should be made available to all parties involved in proximity operations.

3.5.5 Exclusion Zones

Define the exclusion zones (camera, propulsion, etc.) in which either vehicle (Client or Servicer) could cause harm or distrurbance to the other. These may include (but are not limited to):
- Ranges where Servicer lasers could casue damage to CSO optical devices
- Ranges where Servicer thruster plumes could cause attitude disturbances on the CSO
- Ranges where there could be RF interference between the vehicles

3.5.6 EMI Constraints

Define the EMI constraint requirements for safe spacecraft operation in the vicinity of another spacecraft. In the case that space-to-ground communications are occurring during RPO, identify the max RF power density that each spacecraft can survive. Identify the frequencies each spacecraft uses for communications whilst in close proximity.

3.5.7 Prepared vs. Unprepared RPO

Define whether or not the Client Space Object is *prepared* or *unprepared*.

1. Define which prepared features and functions (if any) are present. Prepared spacecraft may be equipped with interfaces and accommodations intentionally designed to enable in-space servicing, such as docking ports, fiducials, and spacecraft-to-spacecraft crosslink communications systems. Identify whether and exactly when the Client Space Object or Servicer Spacecraft will enter a passive attitude control mode (free drift), Identify whether the spacecraft in free-drift can retain gyroscopic stability to ensure its tumbling motion and rate remain low and constrained.
2. Identify any cross-link communication capabilities onboard. Assess whether either of the spacecraft can communicate directly space-to-space with the other. Identify at which range(s) RF and/or optical communications can be safely used. By incorporating detailed cross-link communication assessments into RPO mission planning, operators can improve cooperative navigation accuracy, enhance autonomous safety capabilities, reduce dependence on delayed ground control intervention, and establish more resilient operational safeguards for both Servicer and CSO throughout all phases of proximity operations.
3. For unprepared RPO, detail the information you have from the client about the CSO. Ensure that you obtain full specifications for any features that will be used in place of fiducials. Define a contingency plan of action for proceeding if these features do not match their specifications when observed.

3.5.8 Sensors and Fiducials

Define the sensors and fiducials which are being used. Identify which range(s) they are designed to be used within, and what minimum requirements are needed to successfully utilize them. Define what functional redundancy is available through dissimilar systems. Refer to AIAA S-155 (Spacecraft Fiducial Markers) standard for best practices.
Identify the relationship between fiducial markers and important reference frames, such as the vehicle CG and principal axes, or the desired 6-DOF relative pose.

3.5.9 Passively Safe Trajectories

Identify whether or not the trajectory is passively safe, and for how long it is passively safe, along with the criterion for determining when the trajectory ceases to maintain passive safety. Identify whether it is safe in the presence of failed maneuvers or partially completed maneuvers.

3.5.10 Forced Motion Trajectories

When possible, consider designing active forced motion trajectories close to the client to be passively safe for as long as possible, by limiting the maximum relative velocity as function of relative distance. This way, even at the event of a loss of control, the Servicer will remain with a residual velocity that will put it on a safe free-drift orbit.

3.5.11 Trajectory Propagation

Identify the method used for real-time trajectory propagation during proximity operations. Identify the algorithms being used and what errors are induced.

3.5.12 Collision Avoidance Mechanisms

Define what occurs when the trajectory is no longer passively safe, and what procedures are in place to protect the Client Space Object and Servicer Spacecraft. A trajectory can be considered no longer passively safe if the collision probability is outside of norms for an orbital regime. For example, in LEO this is 1e-4 for RPO Mission Safety and 1e-5 for RPO Environmental Safety[15].

Identify the collision avoidance mechanisms in place, and what onboard systems are required to be functional for proper function of the collision avoidance system. Identify which of these are autonomous vs ground commanded, and the fault tolerances of these systems. Determine the response times required to execute these procedures, and how this compares to the time until inadvertent contact.
Identify whether the Servicer or Client will act first for abort maneuvers. Define the use-cases for both active and passive abort and collision avoidance.

3.5.13 Servicer Communications & Autonomy

Identify the communications used both between the Servicer and ground, and any crosslinks between the Servicer and CSO. The Servicer spacecraft should have sufficient onboard autonomy such that when communications are not available to the ground and/or the CSO, it is able to continue with the mission trajectory, or enter a safe hold point/state until communications are restored.

3.6 Phase 7.6: Inspection-Only Option

In an inspection-only mission, the two spacecraft will not physically dock or berth with each other. However, the following should be considered above and beyond Phase 7.1 (RPO).

3.6.1 Trajectory & Pose Identification

For the inspection maneuver(s), define the trajectories that the Inspecting (Servicing) spacecraft will be following to satisfy the inspection needs of the Client Space Object. Identify whether or not the Client will be repositioning or reorienting during the inspection, and how this maneuvering could impact the Servicer. Typically, this knowledge would be needed for safety purposes if the Servicer will be approaching nearby to or within a volume bounded by the largest overall dimension of the CSO (e.g., Solar area width).

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[15] Newman, Lauri K. "NASA Conjunction Assessment Risk Analysis (CARA)." *USRA Annual Workshop: Space Situational Awareness*. No. GSFC-E-DAA-TN39817. 2017.

3.6.2 External Influences

Consider the possibility of thruster plume impingement from the Servicer onto the Client, or vice versa. Consider potential RF/EMI interference between the the Servicer and the Client. Identify whether the operational modes of the CSO need to be modified to address these potentially negative interactions.

Consider also the possibility of solar incursion into sensors on the CSO or Servicer during inspection operations, and whether or not this can damage the sensors. Consider not only direct solar inclusion, but also those caused by reflections from solar arrays or other polished surfaces.

3.6.3 Operational State of Client

Define the operational state of the Client Space Object. Identify if the Client is tumbling, or venting gas. Clearly outline the risks of the inspection approach.

3.6.4 Inspection Sensors

Define the sensors and their operating ranges being used for inspection of the Client Space Object. Identify any possible interference these sensors could have with operations of the Client.

3.6.5 Orbital Conditions for Inspection

Define under which orbital conditions inspection will be performed. This can include sunlit only, eclipse only, all lighting conditions, while in view of ground optical or radar tracking, etc.

3.6.6 Communications during Inspection

Define what communication (if any) will be present between the Servicer Spacecraft and Client Space Object during inspection. Identify any direct crosslink communication capability. Identify the communication between MOCs on the ground (if any). Define what periods the Inspector spacecraft will have ground contacts, and what periods it will be inspecting autonomously.

3.6.7 Coordination of Control

For missions where the Client Space Object is an active spacecraft and not debris, define at which point the Client ceases translation maneuvers and other active GNC measures. Identify whether or not there will be any coordinated maneuvering between the Servicer and CSO, and how this would be achieved. E.g., CSO rotates at a specified rate for visual inspection.

When in close proximity for inspection, its important to consider the use of coordinated abort maneuvers, where a pre-planned abort procedure takes into account the relative positions and orientations of the Servicer and CSO to plan an abort that does not result in a collision between the two, nor does it result in plume impingement or inadvertent solar inclusion to critical sensors.

3.7 Phase 10: Departure

In principle Phase 10 (Departure) of the CONFERS Mission Functional Diagram (see Figure 1) is the reverse of Phase 6.2 (Rendezvous), with some additions to cover the differences between Approach and Departure. The Release portion of Release & Departure is covered in the Free Flyer Capture document (AIAA S-158).

3.7.1 Coordination of Control

For missions where the Client Space Object is an active spacecraft and not debris, define at which point the Client resumes translation maneuvers. Identify the Client's operational state postdeparture, i.e. is still operational after departure such as in an slot-relocation mission, or is it non-operational as in a deorbiting/graveyarding mission. Identify if any special attitude requirements exist during the Release and Depart, e.g. Nadir pointing for slot-relocation, or V-bar pointing for graveyarding, and consider any ground communication impacts such an attitude might have.

3.7.2 External Influences

Consider the possibility of thruster plume impingement from the Servicer onto the Client, or vice versa. Consider potential RF/EMI interference between the the Servicer and the Client. Identify whether the operational modes of the CSO need to be modified to address these potentially negative interactions.

Consider also the possibility of solar incursion into sensors on the CSO or Servicer during inspection operations, and whether or not this can damage the sensors. Consider not only direct solar inclusion, but also those caused by reflections from solar arrays or other polished surfaces.

3.7.3 Transition between Relative and Absolute Navigation

The transition point between relative and absolute navigation should be defined. Identify the method used to minimize positional errors during the transition. Define the minimum and maximum range for which the relative navigation system is viable. Define the minimum range at which absolute navigation is viable. Clearly define the overlap (if available) in the sensing regimes to ensure a smooth transition between sensors. Refer to Figure 2 in the Appendix.

3.7.4 Nearby Objects

When planning the departure trajectory for the Servicer, its important to consider not only the object departed from, but any other objects in vicinity to avoid any conjunctions, occlusions, or interference with third-party spacecraft.

4 APPENDIX

This document is built from publications, reference documents/standards, and lessons learned from existing in-space RPO missions. Each of these references are listed here in this Appendix.

4.1 Useful References

4.1.1 Figures

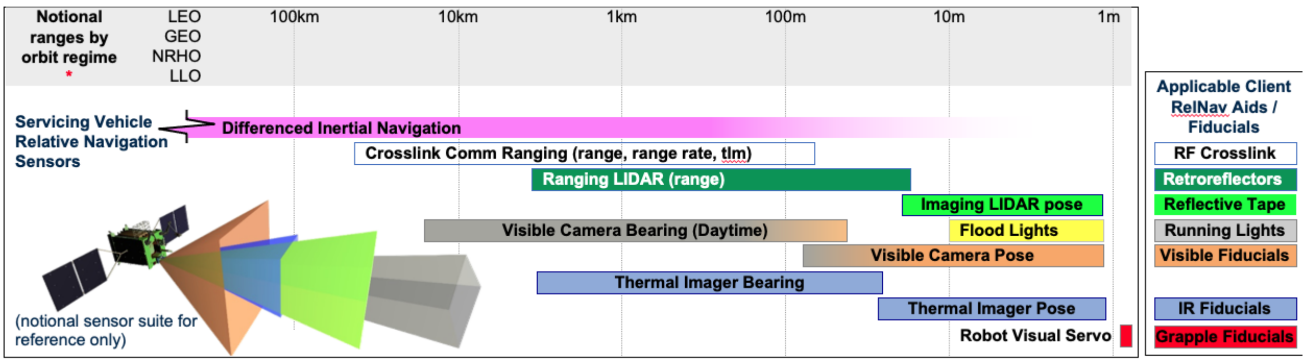

Figure 2: Notional Ranges by Orbit Regime (Courtesy NASA/GSFC)

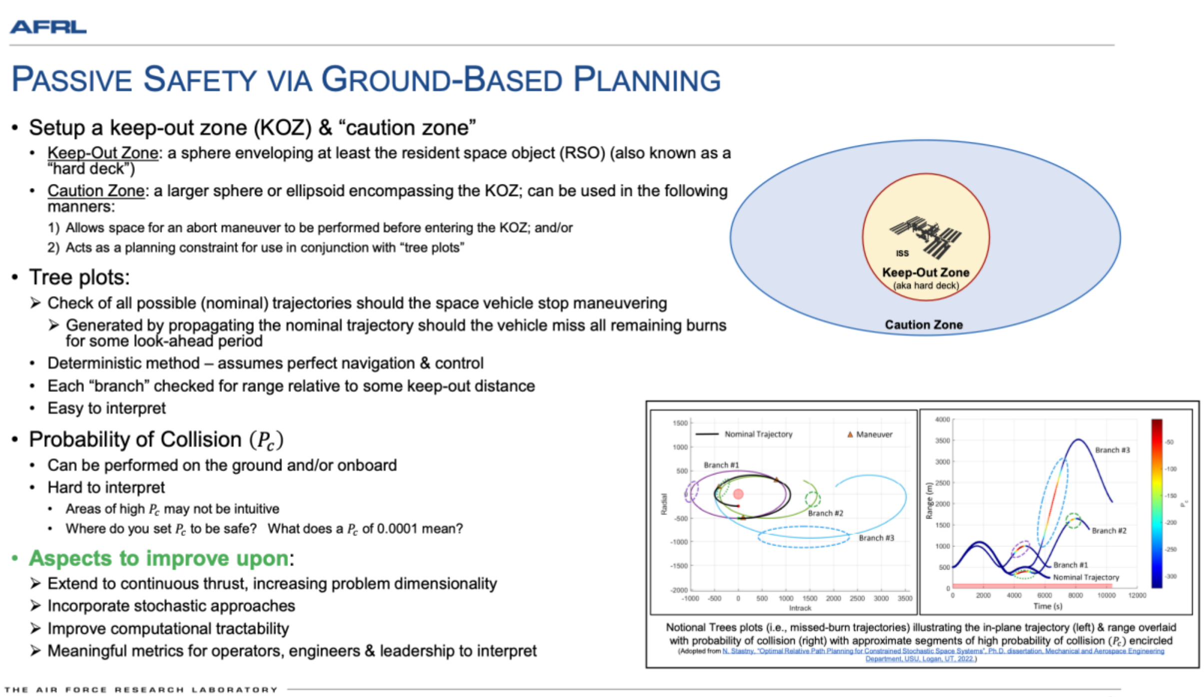

Figure 3: Passive Safety for RPO (Courtesy AFRL)

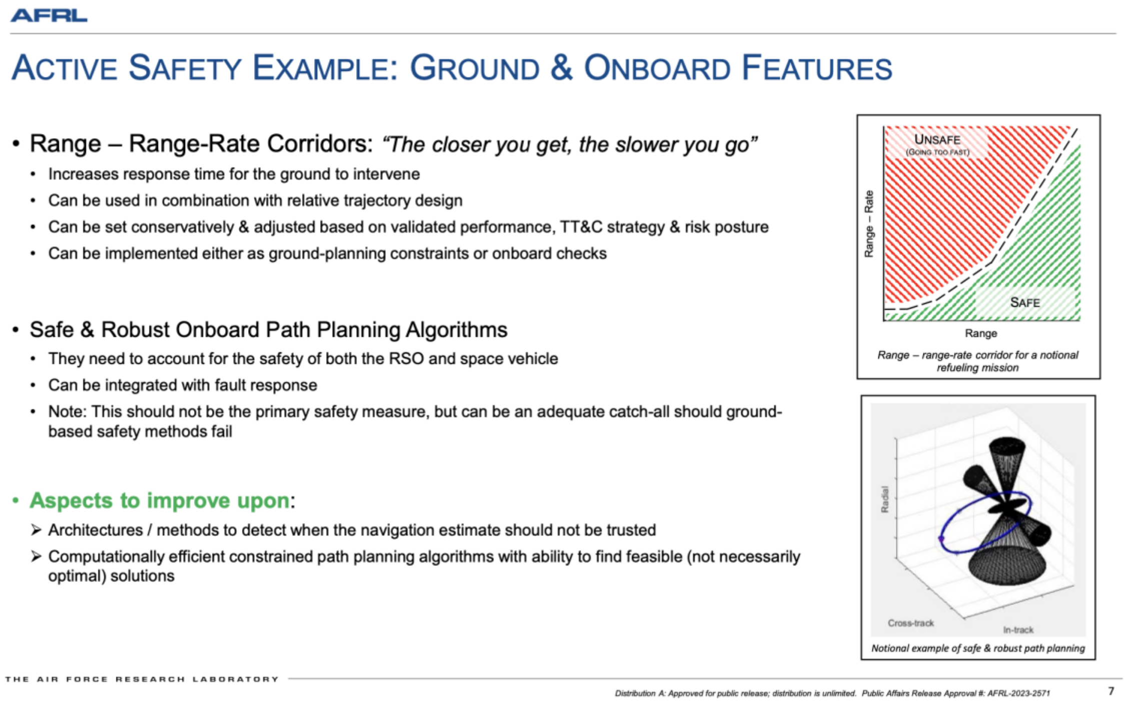

Figure 4: Active Safety for RPO (Courtesy AFRL)

4.1.2 Documents

G-056-1992, Guide to the Serviceable Spacecraft Grasping/Berthing/Docking Interfaces
G-072-1995. Guide for Utility Connector Interfaces for Serviceable Spacecraft
G-042-1991, Guide to Design for On-Orbit Satellite Servicing. [AIAA pulled it, check CONFERS]
AIAA S-158, Prepared Free-Flyer Capture and Release
AIAA S-155, Spacecraft Fiducial Markers
Swiatek, Paulina, et al. "Design Principles for Sustainable Close Proximity Operations." (2019).
ISO 24330 Space Systems – RPO and OSS – Programmatic Principles & Practices
NASA Systems Engineering Handbook
NASA System Safety Handbook
JAXA JERG-2-026 Safety Standard for ON-ORBIT Servicing Missions
ESA-TECSYE-TN-022522 Guidelines on Safe Close Proximity Operations
Japan Space Activities Act, Guidelines on a License to Operate a Spacecraft Performing On-Orbit Servicing
French Space Operations Act, CHAPTER V: SPECIFIC TECHNICAL REQUIREMENTS FOR ON-ORBIT SERVICING
INCOSE Systems Engineering Handbook
STATE OF THE ART AND FUTURE NEEDS IN CONJUNCTION ANALYSIS METHODS, PROCESSES AND SOFTWARE

4.2 Reference Missions

The recommendations in this document are based inputs from the following reference documents and missions. As this is not an exhaustive list of all RPO missions flown, the reader is encouraged to seek out other reference mission documents to feed into their specific mission design.
OSAM-1 RPO Mission (Cancelled)

MEV Mission Extension Mission

DARPA Orbital Express

Orbital Express Rendezvous Lessons Learned

JAXA (formerly NASDA) ETS-VII

JAXA HTV Automated Docking Strategy

JAXA HTV-X Rendezvous Trajectory Design for Lunar Gateway

ADRAS-J

International Rendezvous System Interoperability Standards (IRSIS)

Safe Rendezvous Trajectory Design for the RESTORE-L Mission

Getting In Your Space: Learning From Past Rendezvous and Proximity Operations

4.3 Test Facilities Suited for RPO Validation

Suitable testbeds use air bearing flat floors, offloading robotics, or airborne or ISS-hosted microgravity environments to achieve 6DoF dynamic testing with hardware-in-the-loop.

1. Arkisys + NASA Astrobee ISS Test Facility
2. NASA MSFC Flight Robotics Facility
3. AFRL ROC Lab
4. Naval Research Laboratory (NRL) Laboratory for Autonomous Systems Research (LASR)
5. Lockheed Martin Space Operations & Simulation Center (SOSC)
6. ClearSpace Simulation Facility for RPO Validation
7. SA Catapult UK
8. Massachusetts Institue of Technology Small Satellite Collaborative

9. GMV Platform ART by GMV, Spain
10. JAXA TKSC SATDyn Facility
11. JAXA CAC Air Float Facility
12. Astrovision Lab by Astroscale-IL, Israel
13. Zero-G Parabilic Flight (operates from KSC)
14. SubOrbital Express (Swedish Space Corp)
15. Virgin Galactic Suborbital Research
16. Space Dynamics Laboratory Hardware in the Loop Facility